Performance Analysis of SS312 Stainless Steel in Electrochemical Micromachining Using Copper Tool and NaCl Electrolyte

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Abstract. Stainless steel SS312 is widely used in chemical processing, marine, pressure vessels, and structural components owing to its high strength, corrosion resistance, and thermal stability. Its high mechanical qualities render it difficult to machine using traditional methods. The solution to the complex and burr-free features in SS312 is Microchemical Micromachining (ECMM) on a tool-free controlled anodic dissolution where there is no tool wear or thermal distortion. A tool with an electrolyte parameter interaction significantly affects the productivity, dimensional accuracy, and surface quality. This study examines the effects of voltage, duty cycle, and feed rate on the material removal rate (MRR), overcut, surface roughness (Ra), and taper angle when ECMing SS312 with a copper cathode tool and NaCl electrolyte. The Taguchi analysis indicated that the first factor influencing the MRR was the voltage, followed by the duty cycle and feed rate. The MRR increased with voltage up to 12 V, reaching a maximum of 0.0018 g/min, but reduced slightly at 14 V owing to passive layer formation. A higher duty cycle (65%) enhanced the MRR, leading to a minimum increase in overcut and Ra. By increasing the feed rate from 0.5 mm/min to 0.7 mm/min, the MRR was increased, and excessive feed caused minor dimensional deviations. The optimal setting for maximum MRR was obtained at 12 V, 65% duty cycle, and 0.7 mm/min feed, while smoother surfaces were achieved under 14 V and 55% duty cycle. Higher voltage and duty cycle help in material removal, and moderate parametric combinations are preferable for minimizing the overcut, taper, and surface roughness.

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1. Introduction

Electrochemical machining (ECM) and electrochemical micromachining (ECMM) have emerged as technologies for fabricating intricate and high-precision features on hard-to-machine materials. ECM-based processes are superior for achieving precise three-dimensional micro- and nanoscale structures without thermal damage or tool wear [1]. The EMM process efficiency depends critically on the control of anodic dissolution, microtool design, power supply characteristics, and electrolyte dynamics [2]. ECMM has demonstrated significant potential for burr-free machining, thin-foil structuring, and the formation of high-resolution microstructures, although its industrial adoption still requires improved stability, microtool conditioning, inter-electrode gap regulation, and reduction of stray material removal [3-5]. ECMM has been widely applied for producing tapered, reverse tapered, and ultra-small micro-holes, with researchers demonstrating holes as small as a few micrometers [6]. High-frequency delivery of power, polarization control, and electrolyte modification to enhance machining stability and surface integrity are the most important [7-9]. More recent developments, such as better electrolyte formulations, pulsed-power processes, and optimizing microtools, have increased the accuracy and consistency of machining a wide range of alloys to higher levels [10-12]. Based on these premises, several recent studies have expanded the ECMM to advanced superalloys. Interestingly, a high-speed machining rate and geometrical accuracy of the ECMM Co-Ni-Cr-W superalloy were achieved using optimal pulse parameters and electrolyte strategies [13]. The effect of tool material on the performance of micro-drilling [14] of A286 superalloys. The surface integrity of the ECMM A286 alloy was investigated, and it was demonstrated that the pulse conditions controlled the recast-free, smooth micro-features [15]. The dual-fluid system-assisted ECM with the assistance of magnetic flux enhances the flushing performance, removal of debris, and quality of stainless steel surfaces; hence, the significance of the interaction between fluids and fields in ECMM [16]. Although there have been tremendous advances in ECMM with stainless steels and nickel-based superalloys, there is still a shortage of research specifically on SS312. SS312 has a key application in aero-engine, miniature flow-control devices, fuel-injection systems where high aspect ratio, low-taper micro-holes with high surface integrity are important. Nevertheless, a gap in knowledge about this alloy exists owing to the absence of systematic studies correlating parameters such as voltage, feed rate, duty cycle, and electrolyte properties to machining responses such as MRR, overcut, surface roughness, taper angle, and so on. The proven advantages of improved electrolyte formulations of tool material strategies and parameter-sensitive surface integrity control are all-around a detailed study is required to SS312.The formation of machining windows supports precise micro-feature fabrication, improved productivity, and reliable industrial deployment of ECMM for SS312.

2. Materials and Methods

The ECMM setup used for the performance of drilling micro holes is depicted in Figure 1. A 1 mm thick SS312 stainless-steel sheet was selected as the anode material, and a dedicated fixture was designed to hold the 5 × 5 cm workpiece inside the electrolyte chamber, as shown in Figure 2. Based on the preliminary trials and established machining behavior of stainless steels, NaCl was chosen as the electrolyte because of its effective anodic dissolution characteristics and ability to provide stable machining conditions without inducing passivation. For this, a NaCl-based aqueous electrolyte was prepared at appropriate concentrations and circulated into the machining zone to ensure uniform dissolution during the pulse ON time and efficient removal of heat and debris during the pulse OFF time. A copper cathode tool with a diameter of 0.8 mm, as shown in Figure 3, was employed for micro-drilling operations because of its high electrical conductivity and stable electrochemical behavior under pulsed ECM conditions. The tool was aligned precisely with the workpiece, ensuring complete submergence to facilitate uniform electrochemical action. Three input parameters, namely voltage, duty cycle, and feed rate, were identified as enablers that affected the performance of the ECM. The machining parameters were as follows: voltage of 10, 12, and 14 V; duty cycle of 45, 55, and 65 %; and tool feed rate of 0.5, 0.6, and 0.7 mm/min. These parameter combinations were coded by the ECMM control interface, and the inter-electrode gap and rate of circulation of the electrolyte were kept constant during the study. An orthogonal array of L9 Taguchi was used to conduct the experiments in an efficient organization within the given parameter space. The output measurements taken to determine the effect of the process parameters on the machining performance and geometrical quality were the material removal rate (MRR), overcut, taper angle, and surface roughness (Ra), which were measured during each trial. L9 set of experiments was performed on the copper electrode, and the corresponding output responses MRR, Ta, OC, and Ra were recorded.

Fig. 1. Electrochemical micromachining station used for micro ECM drilling

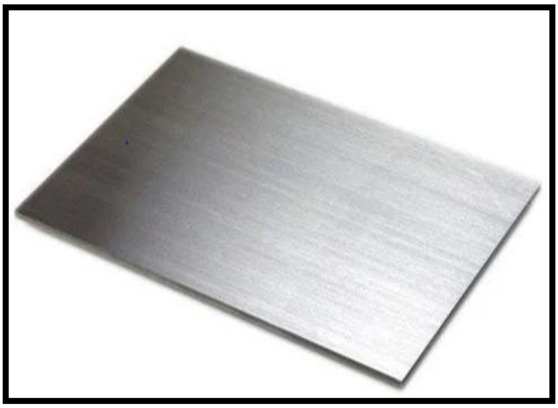


Fig.2.SS312 Workpiece

Fig. 3. Copper Hollow tool

The selected input enablers and their chosen levels are listed in Table 1.

Table 1. Electrochemical micro drilling parameter with levels

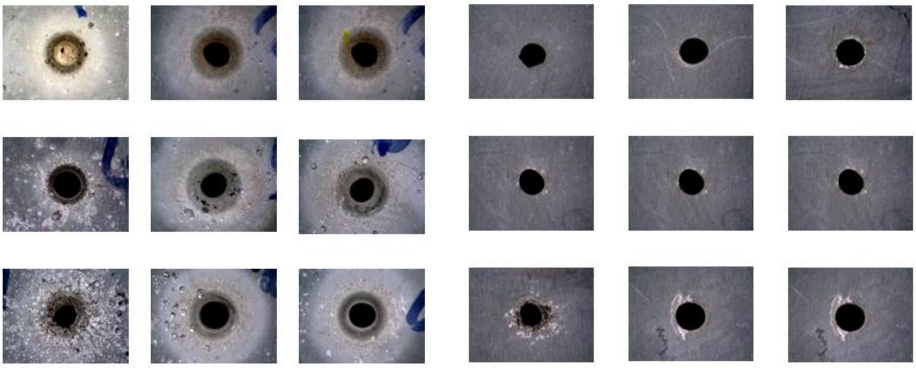
S.No.	Input	Level I	Level II	Level III
1.	Voltage	10	12	14
2.	Duty cycle (%)	45	55	65
3.	Feed rate	0.5	0.6	0.7

Table 2 presents the L9 orthogonal array, listing the experiment numbers along with their corresponding input parameter combinations generated using Taguchi's design of the experiments. The selected parameter levels were finalized based on several preliminary trial runs conducted on the ECMM setup to ensure stable machining conditions and measurable response variation.

Table 2. Experimental plan and runs

ExperimentNumber	Voltage (V)	Duty Ratio	Feed Rate (mm/min)
1.	10	45	0.5
2.	12	55	0.5
3.	14	65	0.5
4.	10	55	0.6
5.	12	65	0.6
6.	14	45	0.6
7.	10	65	0.7
8.	12	45	0.7
9.	14	55	0.7

The entry and exit diameters of the µ-holes shaped by the copper tool were measured using a video measuring system (VMS), and the VMS images are shown in Figure 4.



Entry Side of Micro holes (1-9) **Exit Side of Micro holes (1-9)**

Fig.4VMS images showing the entry and exit sides of microholes fabricated using various cathode tools

3. Results and Discussion

3.1 Parametric influence on Material removal rate

The MRR was determined using the weight-loss method. The weights before and after machining were noted, and the MRR values were calculated. The formula used was

$$\mathrm{MRR} = \frac{W_b - W_a}{T * \rho} \qquad (1)$$

where = weight before machining (mg), = weight after machining (mg), ρ-density, and was recorded in machining time (min). The MRR plot is shown in Figure 5. It is evident from the experiments that the material removal rate is lower than that of the coated and etched tools. It is also noted that an increase in electrolyte concentration and voltage increases the MRR. Voltage plays an important role in controlling the machining rate and surface characteristics in Electrochemical Machining (ECM). In the present experiments using a NaCl electrolyte with a copper workpiece and SS312 tool, it was observed that the material removal rate (MRR) generally increased with voltage up to 12 V and then slightly decreased at 14 V. The average MRR values at 10, 12, and 14 V were 0.000831, 0.001881, and 0.001034 g/min, respectively. This demonstrates that a moderately high voltage (12 V) has better electrochemical dissolution and efficiency for the removal of metals.

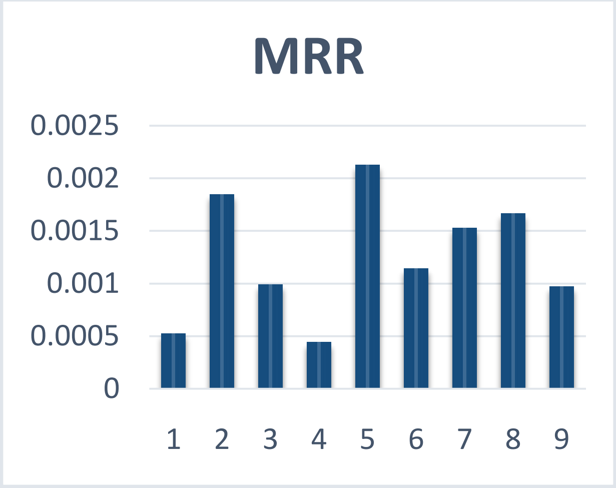


Fig. 5.MRR Plot

The duty cycle is an important factor in machining performance because it dictates the ratio of the ON time in any given pulse period. In this experiment, the MRR increased with the duty cycle, and the mean value was maximum at a 65% duty cycle (0.001483 g/min). An increased duty cycle corresponds to an increased anodic dissolution rate and a higher MRR as the current flow in each pulse increases.

The feed rate determines the speed at which the tool approaches the workpiece during ECM. Increasing the feed rate from 0.5 mm/min to 0.7 mm/min increased the average MRR from 0.001121 g/min to 0.001389 g/min. Higher feed exposes more fresh surface to the electrolyte, allowing higher dissolution rates; however, very high feed can cause unstable machining due to insufficient electrolyte replenishment.

3.2 Parametric influence on overcut

The overcut increased with increasing voltage from 0.494 mm at 10 V to 0.775 mm at 12 V, owing to higher lateral dissolution at elevated potentials. However, at 14 V, the overcut slightly reduced to 0.686 mm, indicating that localized gas formation and passivation at higher voltages might have reduced uniform dissolution. However, continuous exposure to the electrolyte also promoted side etching, leading to a slight increase in the overcut (average 0.686 mm at 65%). The surface roughness showed a mild increase at higher duty cycles owing to non-uniform dissolution and gas bubble formation at the machining gap. The overcut increased marginally from 0.633 mm to 0.683 mm with increasing feed, as shown in Figure 6, indicating higher lateral dissolution because of the increased current density.

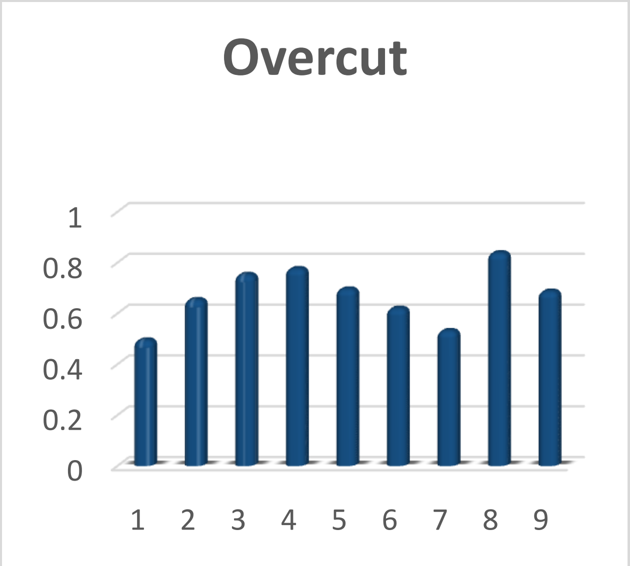


Fig. 6. Overcut Plot

3.3 Effect of tool materials on taper angle

The taper angle tends to increase with voltage up to a certain level, as a higher voltage enhances anodic dissolution and promotes more lateral material removal near the top of the machined hole. Beyond the optimum voltage, the formation of gas bubbles and localized passivation reduced uniform dissolution, slightly lowering the taper angle.

Increasing the duty cycle increases the effective current-on time per pulse, leading to greater material removal near the entry region of the workpiece, thereby increasing the taper angle. However, this may result in an inadvertent high duty cycle, leading to an unreliable flow and decreased machining uniformity, leading to a large taper in high voltage (14 V) and high duty cycle (65%) conditions, and a smaller and more consistent taper in low feed rates and moderate voltage conditions, as illustrated in Figure 7.

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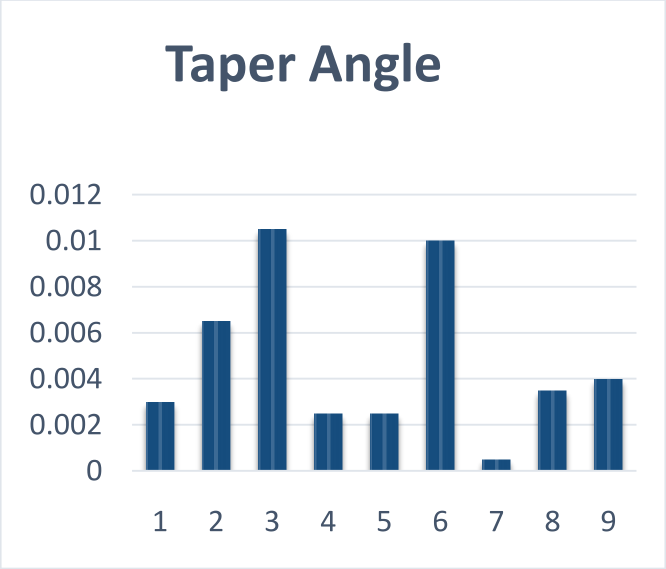

Fig. 7. Taper Angle Plot

3.4 Parametric influence on Surface roughness

The roughness (Ra) of the surface exhibited an opposite pattern to the higher voltage (14 V), which resulted in a smoother surface (average Ra = 0.152 um), whereas a low voltage (10 V) produced rougher finishes (average Ra = 0.280 um). The mean surface roughness of the entry side of the microhole was recorded using a 3D surface profiler, and the values are shown in the machined microholes in Figure 8.

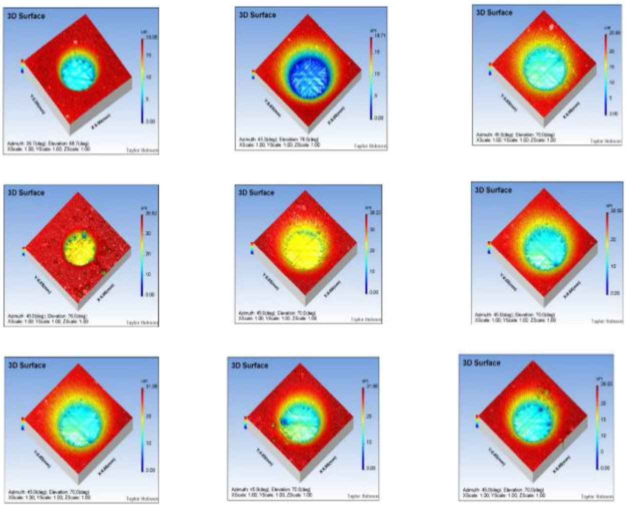

Fig. 8.3D surface roughness plots of entry side of machined micro holes

Thus, moderate voltage contributes to the improvement of MRR, and an increase in voltage leads to an improvement in surface finish because of the constant formation of anodic films. At duty cycles of (45-55 percent) the machining zone exhibited improved flushing and reduced turbulence, leading to reduced Ra (0.145-0.248 um). Hence, an increased duty cycle is an asset to MRR but can cause minor degradation in dimensional accuracy and surface finish. Surface roughness behavior was variably exhibited at intermediate feed (0.6 mm/min) as a result of turbulent flow and poor flushing; however, as the feed increased (0.7 mm/min), this behavior decreased, possibly because of less exposure time and smoother material removal. Therefore, middle-high feed rates are beneficial for increasing the MRR and do not have a major impact on the surface finish. The information on the average surface roughness is shown in Figure 9.

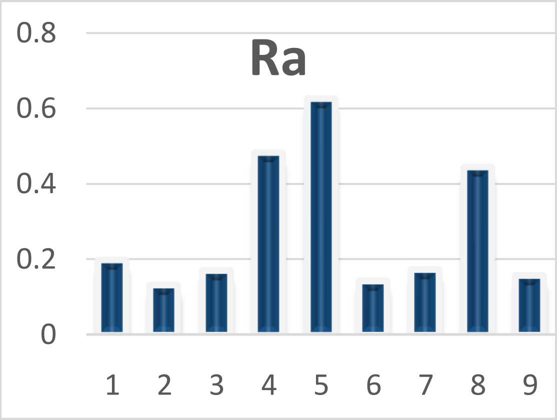

Fig. 9. Average surface roughness Plot

4. Conclusion

The combined analysis shows that the duty cycle is the most determining factor in the material removal rate (MRR), followed by the feed rate and voltage. There was a weak correlation between the overcut and surface roughness, and possibly a superior-quality surface finish with an increased overcut owing to the increased lateral stray dissolution. To maximize the MRR, the combination of the best parameter setting was found to be 12 V, 65% duty cycle, and a feed rate of 0.7 mm/min because all these parameters helped maximize the charge transfer and rapid dissolution of the anode. The reduction of surface roughness is achieved by reducing the dissolution and stabilizing the inter-electrode gap acquired at 14 V voltage, 55 percent duty cycle, and a controlled feed rate of 0.5-0.6 mm/min. To achieve a reduced overcut and better dimensional accuracy, a lower voltage (10 V) and a 45 percent duty cycle are necessary because they restrict side wall dissolution. The obtained results indicate a trade-off between the machining productivity and feature quality in the ECMM of SS312 in copper cathode and NaCl electrolytes.

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Writing – Review and Editing: Karthick, Harikrishnan
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